RESEARCH DEPARTMENT

THE MEASUREMENT OF THE FLOW-RESISTANCE OF ACOUSTIC MATERIALS

Report No. B-061

(1955/14)

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SUMMARY

This report describes methods developed for the measurement of the flow resistance of acoustic materials under direct and alternating flow conditions.

1. INTRODUCTION.

Porous materials such as mineral wools, fabrics and open scrims are widely used for acoustic treatment, and the performance of a material of any one of these types can be to some extent predicted from a knowledge of the resistance offered by it to the passage of air.

The flow resistance of a laminar material is defined as the quotient of the pressure difference between its surfaces and the volume of air flowing through unit area in unit time. It has the physical dimensions $[M][L]^{-2}[T]^{-1}$. In the case of a continuous medium, resistivity is defined as the quotient of the pressure gradient in a specified direction and the volume flow per second per unit area perpendicular to the specified direction. The physical dimensions are $[M][L]^{-3}[T]^{-1}$. The resistance of a laminar material is often expressed as a specific resistance, the non-dimensional ratio of its resistance to the characteristic plane-wave resistance (viz. velocity × density) of the medium in which it is placed.

The value of the flow resistance of a material may vary according to the conditions of measurement or use. In most materials the passages through which the air is able to flow are so small that turbulent flow occurs well within the normal range of sound pressures. The relation of volume flow to pressure gradient under these conditions is non-linear and the quotient will vary with the applied pressure.

Any method of measuring the flow resistance of a material must, therefore, operate at pressures appropriate to the use to which the material is to be put. Acoustic absorbers for broadcasting studios should be effective at pressures between 0·2 and 50 dynes/cm^2 and this has been assumed as the valid pressure range in designing the apparatus described below.

Measurements may be made with direct or alternating flow. Direct flow determinations are made by a method corresponding closely with the definitions given above; i.e., the rate of flow of air through a known area of the sample is measured when a known pressure difference is maintained between the opposite surfaces. Alternating flow determinations can be made by covering the neck of a Helmholtz resonator with the material and observing the alteration in its frequency characteristic.

2. DESIGN OF DIRECT-FLOW MEASURING APPARATUS.

2.1. General Design Considerations.

The apparatus here described was designed to carry out measurements over the pressure range 0·2 to 50 dynes/cm^2. For practical purposes the interesting range of flow resistance is from about 0·2 to 200 c.g.s. units; below this range, the material if used as a sound-absorber, will be poorly matched to the radiation resistance presented to it by the air unless it is covered with a perforated board of small percentage open area to increase its effective resistance, while above this range the peak absorption will diminish rapidly. From the above ranges of pressure and flow resistance it follows that flow rates from 10^{-3} to 250 cm^3/sec may be encountered over an area of 1 cm^2. By making provision for sample areas from 1 cm^2 to 100 cm^2 and for combining thin samples up to 10 in number in cascade, it is possible to confine the volume flow to within the range 0·1 to 100 cm^3/sec.

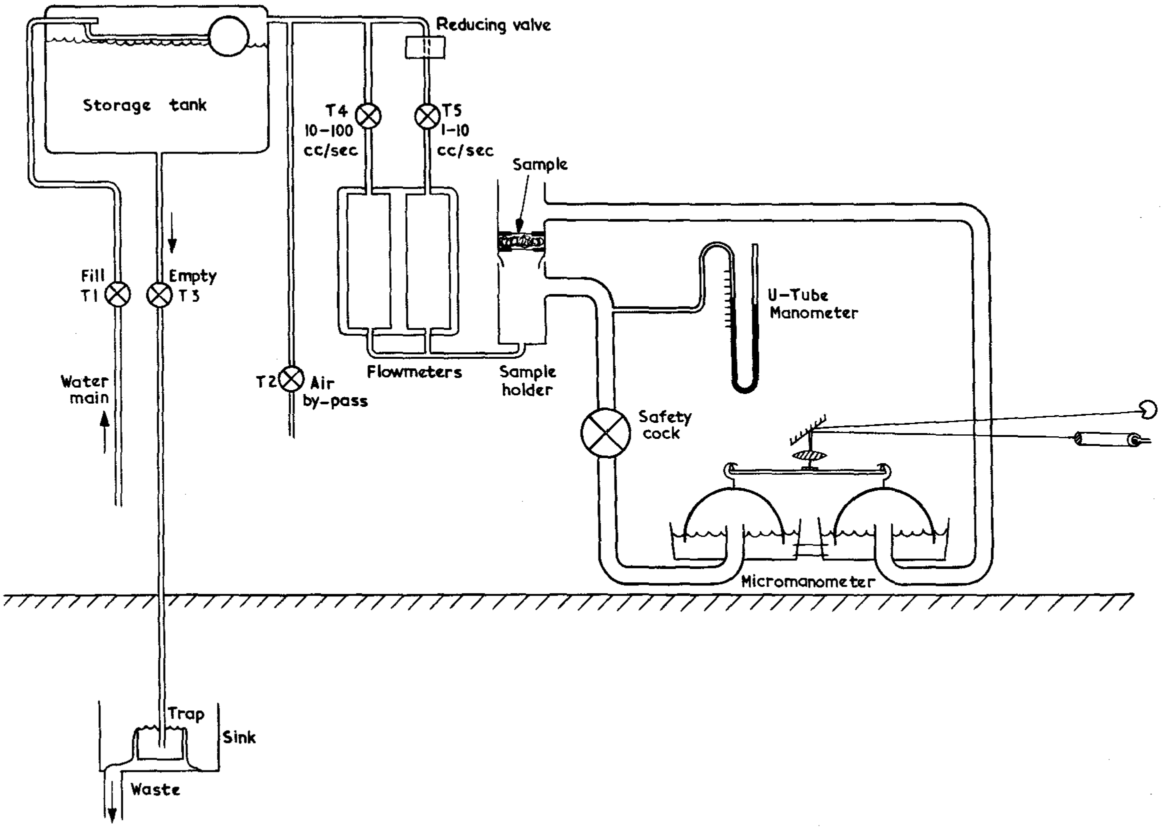


Fig. 1 - Apparatus for measurement of direct flow resistance

Fig. 1 is a diagram of the whole apparatus. It consists of four parts:

1. Means for drawing air at a predetermined constant speed through the sample.
2. An air-flow meter.
3. The sample holder.
4. Apparatus for measuring the pressure difference between the two faces of the sample.

2.2. The Air-flow Generator.

A closed galvanized storage tank, fitted with a ball-valve to limit water level, is filled by opening a tap T1 to connect to the main water supply, the air exit tap T2 being left open. T1 and T2 are then closed and a drain-tap T3 is opened, allowing the water to escape. The lower end of the drainage pipe is taken into a syphon trap which prevents air from entering the bottom of the pipe and reducing the effective head of water in it. The water then flows out at a steady rate, drawing air into the top of the tank through a pipe which is connected through the flowmeters to the sample holder. The rate of flow is controlled by adjustment of T2 and T3.

2.3. The Air-flow Meters.

Two flow meters are mounted side by side, one measuring rates of flow up to 10 cc/sec, the other extending the range to 100 cc/sec. Taps T4 and T5 enable the air to be drawn entirely through either meter as required. The meters, made by the Rotameter Manufacturing Company, are of a standard type, though specially designed for this equipment with respect to range and calibration. In this type of meter, the air passes up a graduated vertical tube about 20 cm in length, the bore of which increases gradually from the bottom to the top. The air flow supports a small hollow aluminium float, shaped like a peg-top, which reaches equilibrium at a position in the tube where the resistance of the annular space between the float and the tube is just sufficient to set up a drag equivalent to its weight. Oblique flutes in the float cause it to spin as the air flows past, so preventing the float from dragging against the walls of the tube. When using the 0-10 cc/sec gauge, the flow is controlled by a reducing valve in series with the main tap.

2.4. The Sample Holder.

The function of the sample holder is to confine the air flow to a known area of the sample of material under test, preventing leakage round and through its edges. The tubes by which the pressures at the two faces of the sample are transmitted to the manometer also terminate in the holder, which must be designed to minimise errors due to local acceleration in the air streamlines. An additional requirement is that it shall be possible to mount several similar samples in cascade. Fig. 2 shows a section through the sample holder. The normal exposed area of each sample is 10 cm^2, the sample or samples being clamped between duralumin ring spacers. The pressure plate, which is drilled with large holes to allow free passage of air, is

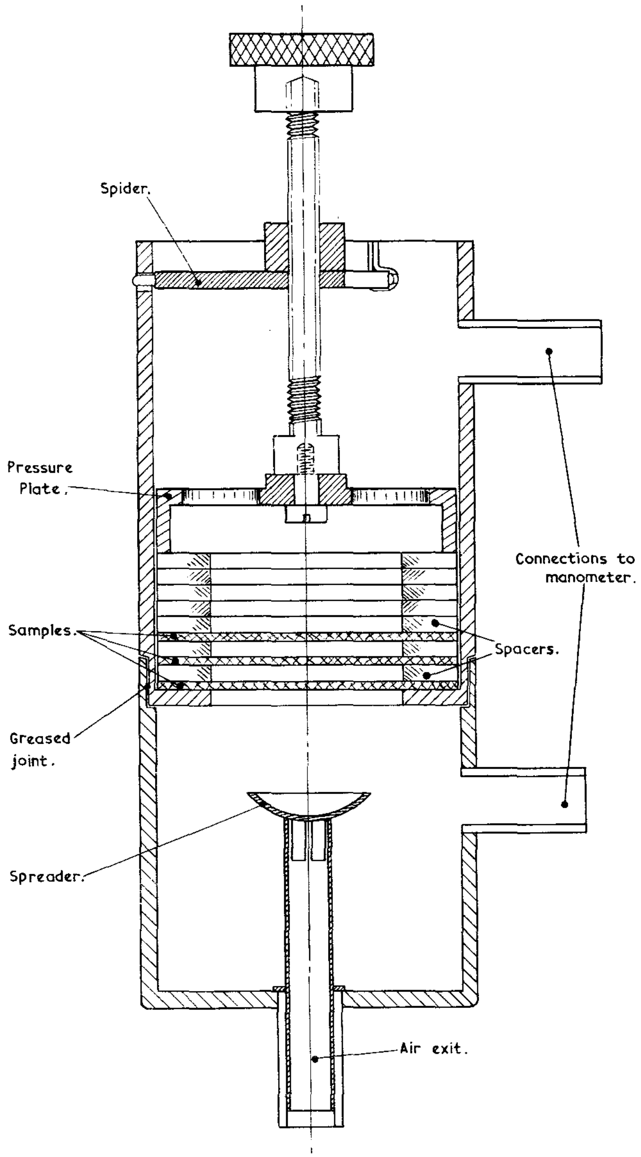


Fig. 2 - The sample holder

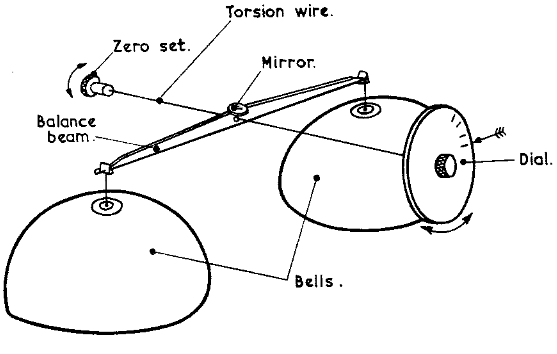
forced against the top spacer by a screw running in a nut which is fixed to a brass spider engaging with bayonet slots in the outer case of the sample holder. A tube in the bottom is connected to the airflow generator which therefore draws air downwards through the sample; the connexions to the manometer enter at the sides in relatively undisturbed regions above and below the sample.

For thick specimens, e.g. of mineral wools, the duralumin spacers are replaced by a tube of 10 cm^2 internal cross-section which is arranged to fit centrally under the pressure plate. A larger sample holder of similar design but of area 100 cm^2 is under construction.

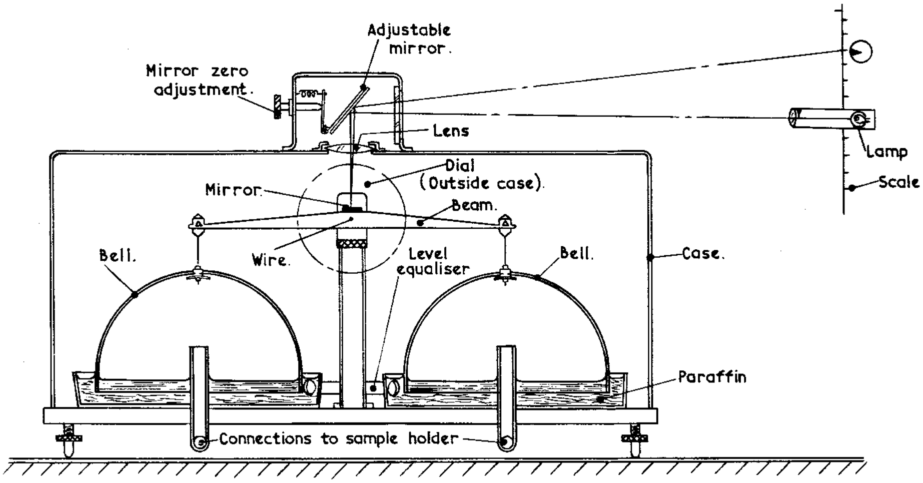
2.5. The Micromanometer.

The measurement of pressure differences below 1 dyne/cm^2 (approx. 10^{-6} atmosphere) requires an extremely sensitive manometer. Various devices have been used to attain this sensitivity: in a tilting manometer the sensitivity depends upon the accurate maintenance of very small angles of slope and is limited by surface tension forces. Numerous attempts have been made to measure very small pressure differences by the use of aneroid barometers using extremely compliant diaphragms and very sensitive methods of measuring the diaphragm displacement. Among such displacement measuring methods are the observation of optical interference fringes and the measurement of the electrical capacitance of a condenser of which the diaphragm forms one plate and a fixed part of the apparatus the other. None of these methods appears from published data to give the required sensitivity, and it was therefore decided to design a micromanometer in which the difference of pressure is calculated directly from the difference between the forces on two equal areas subjected to the two pressures. In essence the method uses two bell-shaped vessels hanging from the arms of a balance and dipping into a liquid. Tubes connect the air enclosed in the two vessels to the spaces between which the required pressure difference is maintained and the force difference is determined by weighing. A commercial manometer of this form is marketed, using a conventional chemical balance but the stated sensitivity was insufficient by a factor of 10. In the arrangement finally used, the conventional balance was, therefore, replaced by a torsion-wire balance, calibration being carried out by suspending known weights on the arms.

Fig. 3 shows the construction of the micromanometer. 3(a) is a perspective sketch of the balance beam, bells and torsion wire. Inequality of pressure beneath the two bells causes the torsion wire to rotate at its middle point, where it is attached to the beam, thus causing equal but oppositely-sensed torsion in the two halves of the wire. It will be seen that in order to restore the beam to its original direction, the calibrated dial at one end of the wire must be rotated through twice the angle of the original displacement of the beam. A mirror mounted at the mid-point of the beam serves in conjunction with a lamp and scale system to indicate the null position of the beam. The sensitivity of this type of micromanometer is limited by errors due to the surface tension forces on the bells and by the buoyancy of the material of which they are made. The effect of variations in surface tension forces is reduced by using kerosene since it has a low surface tension and wets the polyvinyl chloride material well. Buoyancy forces are minimised by using thin-walled material of a specific gravity near that of the liquid and by the adoption of a null method in which the balance arm is returned by a torsion head to its undeflected position.



(a) Perspective view of torsion balance system



(b) Centre section from rear

Fig. 3 - The micromanometer

Fig. 3(b) shows the mechanical arrangement of the apparatus. The beam is machined from duralumin strip and carries hardened steel knife-edges at its centre and ends. The bells are mouldings made from a semi-rigid polyvinyl chloride foil 0·012 cm thick, and suspended from the balance arm on V-slots as in a chemical balance. The torsion wire is phosphor-bronze, of diameter 0·033 cm and length 18·5 cm.

The lower edges of the bells dip into shallow dishes which contain the kerosene and a connecting pipe between the two dishes maintains equality of level.

On the top of the beam a small piece of plane mirror is mounted horizontally, facing upwards. The aluminium case which encloses the manometer carries a lens of 1 metre focal length mounted horizontally above the plane mirror, and a 45° mirror above the lens. This system forms on a vertical scale an image of a translucent arrow, which is carried on a condenser lens forming the front of a lamp-house clamped to the scale mounting, and any movement of the balance arm causes the image to traverse the scale. The 45° mirror is hinged and may be adjusted by means of a screw to set the image at any point in the scale which is to be used as the null point.

For measurements at higher pressure differences the polyvinyl chloride bells, which have a cross-sectional area of 128 cm^2, are replaced by cylindrical aluminium bells of 7·05 cm^2 cross-section.

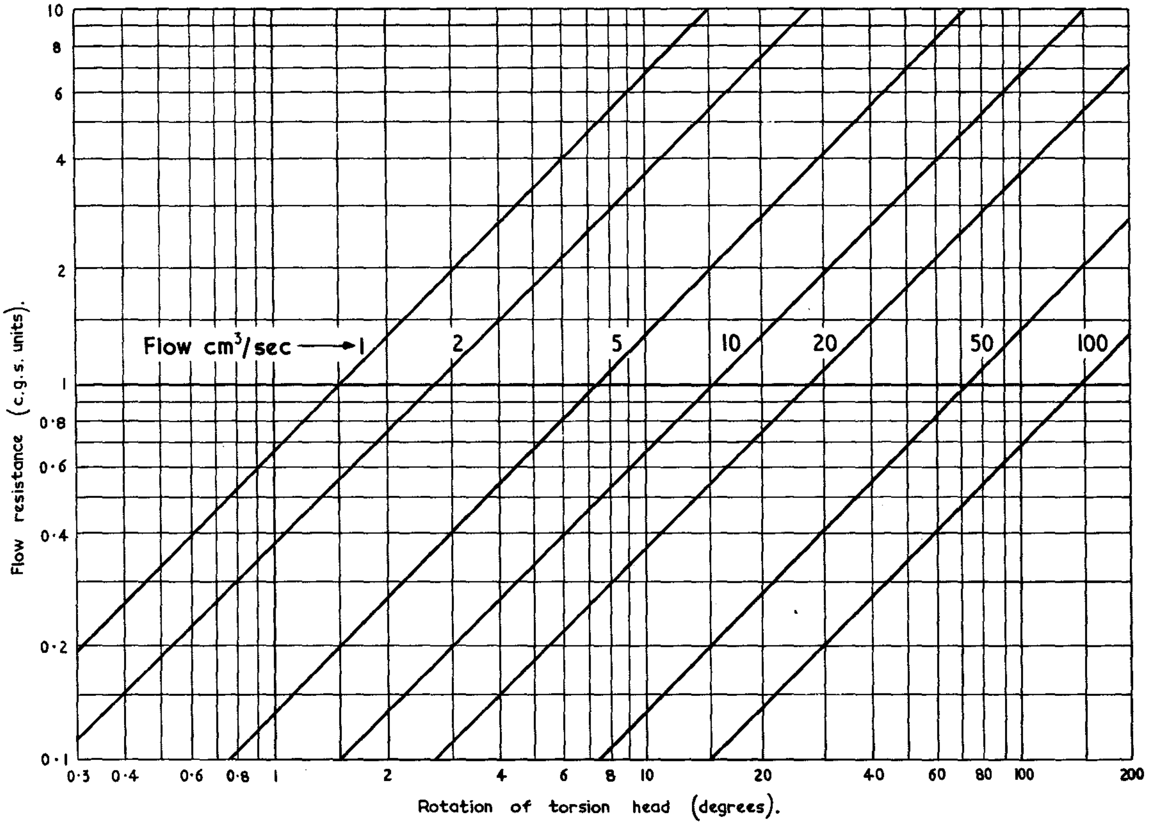


Fig. 4 - Calibration chart. P.V.C. bells (128 cm^2). Sample area 10 cm^2

Figs. 4 and 5 show the calibration charts for the two ranges.

The pressure differences considered are extremely small, being comparable with the difference of pressure between two points in still air separated by only a few centimetres vertical distance. The flow of air in and out of the bells is therefore slow and if the resistance of the connecting tubes is high, the balance will take a long time to reach a new equilibrium position. For instance, a pressure difference of 1 dyne/cm^2 will cause a deflection of about 2 cm in the large bells,

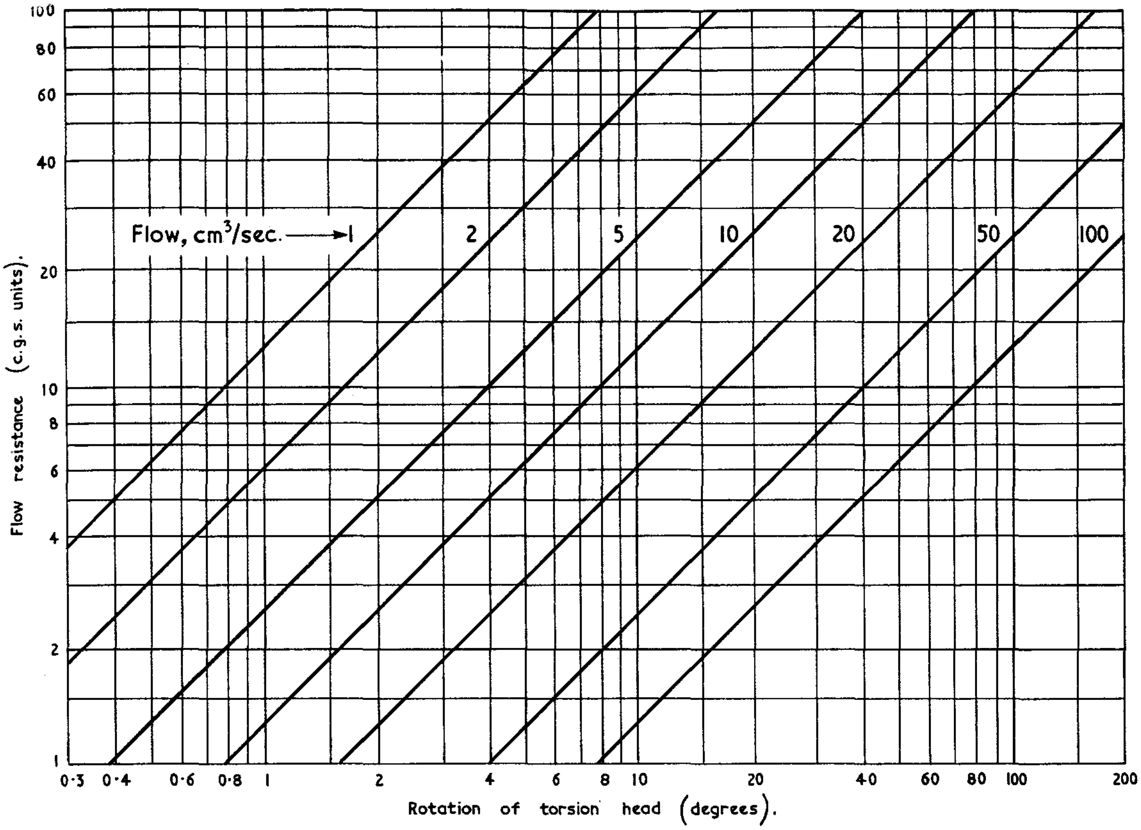


Fig. 5 - Calibration chart. Aluminium bells (7·05 cm²). Sample area 10 cm²

so that 250 cm³ of air must flow through each of the tubes. Calculation shows that if the tubes are 1 metre long with a bore of 5 mm, the pressure difference of 1 dyne/cm² will take over six minutes to complete the transference. In practice, with the null method used, it is not necessary to wait for this transference, but the determination of the null setting was nevertheless found with such tubes to take well over a minute. Wide rubber tubes of 15 mm bore were therefore used for the two connexions between the sample holder and the micromanometer; the time for the transference is now of the order of four seconds only, and the determination of the null point correspondingly faster.

Referring again to Fig. 1, it will be seen that a simple U-tube manometer is also attached to the low pressure connecting tube, and a safety cock of 12 mm bore is inserted between the two manometers. The user is able by this means to check that the pressure difference is within the working range of the micromanometer before opening the safety cock to take a reading.

3. DYNAMIC MEASUREMENTS BY THE HELMHOLTZ RESONATOR METHOD.

3.1. General.

The resistance of a material under actual working conditions may be derived from its influence on the frequency characteristic of a Helmholtz resonator. The resistance thus measured may differ from that measured by steady flow methods because of changes in the configuration or position of the material. For instance, small loose fibres may become aligned with the air stream during direct flow measurement, but oscillate between two extreme positions when an alternating flow is applied. A thin fabric which has a high flow resistance may also give different results if it is inadequately supported, since under alternating flow conditions it will tend to move bodily in the direction of the instantaneous flow; in this case the airflow resistance will be shunted by the resistance of the fabric to flexure.

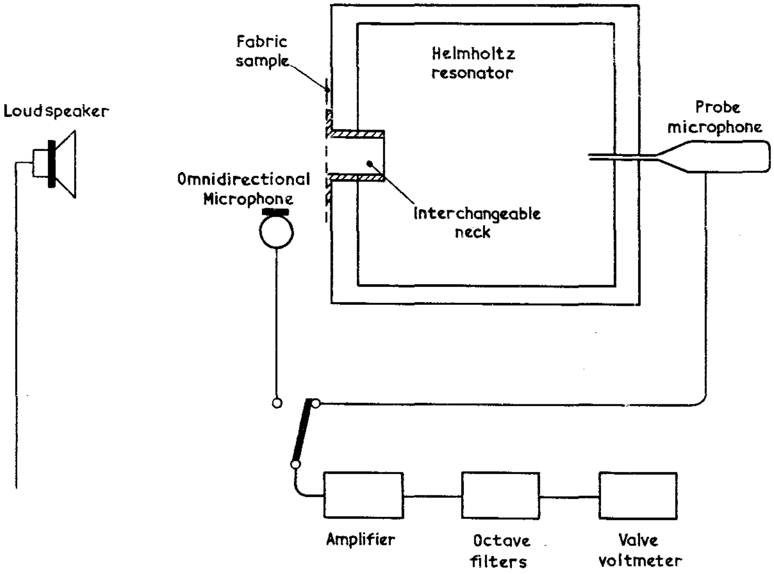


Fig. 6 - Schematic diagram of dynamic measurement

The apparatus is shown diagrammatically in Fig. 6. The probe microphone, amplifier and valve voltmeter are used to obtain a record of the pressure variations in the cavity of the Helmholtz resonator as the exciting tone from the loudspeaker is varied over a range of frequency which includes the frequency of resonance of the resonator.

Theoretically the decay time of the resonator or several features of the resonance curve could be used to derive the resistance of the neck of the resonator but the most convenient and accurate method was found to be a direct measurement of the ratio of the pressure amplitude at resonance inside the cavity to the pressure amplitude of the sound field outside. This ratio is known as the magnification, Q, and is given by the equation

$$Q = \frac{\rho c^2}{\omega V R}$$

where ρ is the density of air, c the velocity of sound, V the volume of the cavity, R the sum of the radiation resistance and the internal resistance of the neck, and $\omega/2\pi$ is the frequency at resonance.

A second microphone is placed outside the resonator as shown in the diagram and with a knowledge of the relative sensitivities of the two microphones, the ratio of the pressures inside and outside at resonance may be derived. This measurement is made with the resonator neck first open and then covered with the material under test.

If R_0 is the total resistance of the system and Q_0 its magnification with the neck of the resonator uncovered, we therefore have

$$R_0 = \frac{\rho c^2}{\omega V Q_0}$$

A similar equation connects R_1 and Q_1, the resistance and magnification after the resistive material has been added. Hence we may write the resistance, R_m, of the material under test as:

$$R_m = R_1 - R_0 = (1/Q_1 - 1/Q_0)\rho c^2/\omega V$$

R_m is then multiplied by the effective area of the sample to obtain the unit-area resistance.

It is found that the position of the external microphone is fairly critical; if placed too near to the neck of the resonator it will be in a region where the streamlines are converging towards the neck and will show a higher pressure at resonance, whereas if too far away it will be affected by non-uniformity in the polar diagram of the loudspeaker and the room acoustics. The best position must be chosen by experiment; if the external microphone is moved slowly away from the resonator towards the loudspeaker, the difference at resonance between the two microphones rises to a maximum and then remains stationary, eventually decreasing again as the microphone approaches the loudspeaker. The nearest point to the resonator neck, normally off the axis, at which the constant condition is obtained, is chosen. With a loudspeaker about 1½ metres from the particular resonator used, the best position in a highly-damped sound measurement room was found to be 6·4 cm in front and 6·5 cm to one side of the neck.

3.2. Behaviour with Resistive Fabrics.

Experiments, using woven fabrics as experimental materials, were carried out to establish whether the method would give a true unit-area resistance independent of area, and whether the resistance so measured varied with the frequency of resonance.

For this purpose two wooden resonators were made, so designed that they could be tuned over a 2:1 range of frequency by changes in volume effected by moving a piston which formed the back of the cavity. The radii of the necks of the two resonators could be varied by inserting flanged brass bushes.

To investigate the effect of the sample area on the measured unit-area resistance, the resistance of the same piece of fabric was measured with two or more different neck diameters, and the influence of frequency was explored by changes in the volume of the cavity.

4. RESULTS OF MEASUREMENTS.

4.1. Effect of Rate of Flow——Direct Flow Method.

Table 1 shows the results of measurements on ten samples cut from the same piece of fabric, each sample having an area of 10 cm². The right-hand column indicates the variation found between similar samples under the same conditions.

TABLE 1

Effect of Volume Flow, 10 cm² sample

Volume Flow	Mean Resistance	Std. Deviation of Mean
5 cc/sec	8·5 c.g.s.u.	0·25 c.g.s.u.
10 cc/sec	9·0 c.g.s.u.	0·22 c.g.s.u.
15 cc/sec	9·0 c.g.s.u.	0·23 c.g.s.u.
25 cc/sec	10·2 c.g.s.u.	0·43 c.g.s.u.

The difference between the results at 5 cc/sec and 25 cc/sec is large in comparison with the standard deviations of the means, and it may therefore be concluded that signs of non-linearity, due presumably to turbulence, are present even at such low flow rates. The original design assumption that all measurements should be made at flow rates comparable with those encountered in practice is therefore justified. On the other hand, the change in mean resistance within the practical working range is not very serious and for the design of acoustic absorbers it may be neglected, so long as the absorbers are not intended for very intense sounds such as those from aircraft test installations. In general, measurements should be made at pressure differences appropriate to the sound-fields likely to be encountered.

4.2. Effect of Area——Direct Flow Method.

Four different fabrics were each tested in sample holders of 1, 2, 5 and 10 sq. cm areas. Each sample was tested at several rates of flow so distributed that the unit-area flow resistance at a velocity of 1 cm/sec could be determined for each area by interpolation. The results were then tabulated as percentages of the unit-area resistance of the 10 sq. cm sample.

The results showed no significant trend in the resistance towards greater or smaller values as the area was increased, and it was concluded therefore that, at any rate in conditions of substantially streamline flow, the volume of air flowing is proportional to the area of the sample.

4.3. Effect of Area and Frequency——Helmholtz Resonator Method.

Table 2 below shows a comparison between measurements made with necks of different diameters and at a number of different resonance frequencies. An examination of this table shows that the measured specific resistance increases slightly with the area of the neck, the increase amounting to 10% for an increase of 120% in the area. There is no significant variation with frequency, and two layers of the same fabric were found to have twice the resistance of a simple layer.

TABLE 2

Effect of Sample Area and Resonance Frequency

One layer of fabric (bandage)

c/s	Neck Area		(cm²)
	5·04	11·4	Mean
195	0·54	0·67	0·60
230	0·62	0·55	0·58
260	0·47	0·49	0·48
Mean	0·54	0·57	0·55

	1·98	5·04	Mean
145	0·52	0·56	0·54
175	0·34	0·55	0·45
210	0·55	0·43	0·49
Mean	0·47	0·51	0·49

Two layers of fabric

c/s	Neck Area		(cm²)
	5·04	11·4	Mean
195	0·94	1·02	0·98
230	1·02	1·06	1·04
260	0·93	1·12	1·02
Mean	0·97	1·07	1·01

	1·98	5·04	Mean
145	1·02	1·06	1·04
175	0·85	1·28	1·07
210	1·12	1·05	1·08
Mean	1·00	1·12	1·06

4.4. Comparison between the Direct Flow and Resonator Methods.

Table 3 summarises the results of a number of measurements on a range of cloths, using both methods of measurements. The direct-flow measurements on each sample were made at two different speeds of air flow, 5 cm/sec and 10 cm/sec.

TABLE 3

Comparison between Direct-Flow and Resonator Methods

Material (All Claire's Dairy Cloths)	Specific Flow Resistance in C.G.S. Units Direct flow 5 cm/sec	Direct flow 10 cm/sec	Resonator Method
1120 C	0·16	0·17	0·16
B.4	0·20	0·20	–
Green	0·33	0·37	0·24
Brown Linen	0·40	0·45	0·47
522c Tubular	0·53	0·56	–
Blue	0·64	0·64	0·54
22EB Tubular	0·92	1·04	–
Lilac 3	1·30	1·40	0·74
B.6884	1·45	1·40	–
B.40	1·85	1·90	0·84
Calico	7·6	7·8	1·47

It will be seen that the agreement between the two methods is good in the case of fabrics of low specific resistance, but for denser materials the direct flow indicates increasingly high values.

The explanation for this discrepancy lies in the fact that in the resonator method a dense fabric is moved bodily by the alternating pressure and its direct flow resistance is shunted by its resistance to flexure in series with its mass. Additional evidence for this view is provided by the fact that in the case of the denser fabrics there was observed a decrease in the resonance frequency showing that the effective mass of the neck had been increased.

It is evident, therefore, that fabrics of high density used for increasing the resistance of resonator necks (see for example Ref. 8) should be supported by wire gauze or some similar material to prevent the reduction of resistance from this cause.

5. CONCLUSIONS.

The two methods described here for measuring the direct-current flow resistance of acoustic materials both give valid results for materials of low resistance such as open-woven cloths. The direct-flow method gives values of the unit-area resistance independent of the sample area, while the results for the resonator method are slightly dependent on area, increasing by 10% for about 120% increase of area. The direct flow method gives slightly larger values of resistance if the flow velocity is raised but at normal sound pressures this effect is of little practical importance. Both methods give doubled resistance if two layers of fabric are tested in place of one.

The only substantial difference between the two methods occurs in the measured values of dense fabrics, the resonator method giving low values because of movement of the fabric as a whole. This phenomenon is of practical importance since it enables one to find out by experiment the measures needed to prevent movement when the fabric is used to adjust the resistance of a Helmholtz resonator intended for sound absorption.

6. ACKNOWLEDGMENTS.

The dynamic method of measurement was developed by Mr. F.L. Ward of this department. Others taking part in the investigation were Messrs. K.E. Randall, P.J.E. Harvey, and I. Whyte (now with Standard Telephones and Cables).

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